A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
11 (11.13.1; 11.19.4; 08.08.1; 08.05.1; 08.02.7; 08.05.2)

ASTRONOMY
AND
ASTROPHYSICS
1.2.2008

On the nature of the blue giants in NGC 330 ⋆

Eva K. Grebel[1,2], **Wm James Roberts**[3], **and Wolfgang Brandner**[4]

[1] Sternwarte der Universität Bonn, Auf dem Hügel 71, D–53121 Bonn, Germany, grebel@astro.uni-bonn.de
[2] University of Illinois at Urbana-Champaign, Department of Astronomy, 1002 West Green Street, Urbana, IL 61801, USA
[3] Center for Astrophysical Science, Johns Hopkins University, Box 16329, Baltimore, MD 21210, USA, roberts@coyote.pha.jhu.edu
[4] Astronomisches Institut der Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany, brandner@astro.uni-wuerzburg.de

Received Oct 19, 1995; accepted Nov 15, 1995

Abstract. The young SMC cluster NGC 330 contains a number of blue stars that lie above the main-sequence turnoff found from our isochrone fitting and below the position of the blue supergiants. We used our own, new spectroscopy and published data on these stars to investigate their possible nature. Problems in interpreting the evolutionary status of the blue giants have been found in several preceding studies. In theoretical H-R diagrams, these stars lie in the rapidly traversed post main-sequence gap, similar to the unexpected concentration found by Fitzpatrick & Garmany (1990) in the H-R diagram of the LMC.

We argue that these stars probably are core H burning main-sequence stars that appear as blue stragglers resulting from binary evolution as described in the simulations of Pols & Marinus (1994) and effects of rapid rotation. Many of the blue stragglers are Be stars and likely rapid rotators. We suggest that there is evidence for the presence of blue stragglers also in NGC 1818, NGC 2004, and NGC 2100. We point out that blue stragglers may be a general phenomenon in the CMDs of young clusters in the Magellanic Clouds and discuss the implications for IMF and age determinations.

Key words: Stars: Hertzsprung-Russell diagram – Stars: early-type – Stars: blue stragglers – Stars: emission-line, Be – Galaxies: star clusters – Galaxies: Magellanic Clouds

1. Introduction

A few years ago, we started a project to determine ages, metallicities, and reddenings of distinct stellar populations employing a newly developed technique of simultaneous multi-colour isochrone fitting (Roberts 1996, Grebel et al. 1994a). When applying this technique to the young cluster NGC 330 in the Small Magellanic Cloud (SMC), we found a number of stars above the main-sequence turnoff, as indicated by our isochrone fit, but below the location of the blue supergiants (Sect. 2).

When only photometric data are available, these bright blue stars would usually be considered main-sequence stars, which implies that either the cluster is much younger than our simultaneous multi-colour isochrone fit shows or forces the conclusion that there is a considerable age spread in star formation times. Spectroscopy is needed in order to investigate the nature of these stars. We therefore obtained spectra to properly classify these stars (Sect. 3).

In addition to our own spectral classifications we make use of previously published classifications (Sect. 4). These classifications and determinations of surface gravities and effective temperatures place these stars where one would not expect to find so many: in the post main-sequence gap of the Hertzsprung-Russell diagram (H-R diagram).

In the following, we define main-sequence stars as stars in the core H burning phase. When talking about "ordinary" main-sequence stars we are referring to stars undergoing the usual, undisturbed main-sequence evolution typical for single stars, to which also the Geneva evolutionary tracks pertain. According to these models, an ordinary main-sequence star in the turnoff region of a 20-Myr isochrone has a $\log g$ value of 3.7 to 3.8. Of course neither of these values nor a mere spectral classification alone can tell whether a star is core H burning or not.

We shall refer to the area redward of the main sequence as post main-sequence gap or blue Hertzsprung gap. This area lies between the terminal-age main sequence (TAMS) and the area where the blue loops of the supergiants occur. Precise size and location of the gap depend on the stellar models used. According to stellar evolution theory, this region is traversed very quickly (see, e.g., Langer & Maeder 1995 for time scales) making it highly unlikely to find a large number of stars there, or even any stars.

In Sect. 5 and 6 we discuss whether the blue stars above the main-sequence turnoff and below the blue supergiant locus are evolved stars or main-sequence stars. In Sect. 7 we review indications that NGC 330 is not an exception among young Magel-

Send offprint requests to: E.K. Grebel, Sternwarte Bonn

⋆ Based on observations taken at the European Southern Observatory, La Silla, Chile

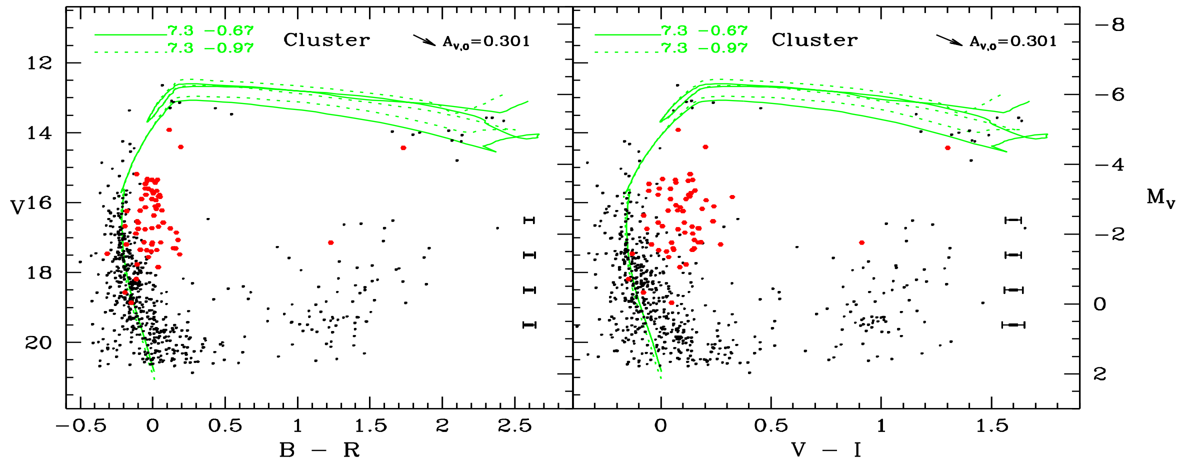

Fig. 1. Colour-magnitude diagrams of NGC 330 for stars within a radius of 22 pc around the cluster center. Outside this radius, the number density of stars is constant; i.e., we no longer expect a significant contribution from cluster members. Be stars are indicated by fat dots. Error bars are also plotted for each diagram. Superposed are our Geneva isochrones (Schaller et al. 1992, Charbonnel et al. 1993) transformed by us to the observational plane (Roberts 1996, Grebel et al. 1994a). These isochrones fit the location of the blue and red supergiants as well as the main sequence. The main-sequence turnoff is located at $V \approx 15.6$ mag. A number of blue stars is visible above the main-sequence turnoff defined by the isochrone and below the position of the blue supergiants.

lanic Cloud clusters in containing blue giants. The implications for the upper IMF and age determinations are discussed in Sect. 8 and 9.

2. The photometric data

We obtained our photometric data with the 2.2m MPIA telescope at ESO, La Silla, Chile, on 14 Nov 1992 and on 08 Oct 1993. We used the ESO Faint Object Spectrograph and Camera (EFOSC II) with a 1024 × 1024 Thomson chip (ESO # 19). Pixel scale was $0\farcs332$ (unbinned) resulting in field of view of $5\farcm7 \times 5\farcm7$. We obtained short and long exposures in Bessel UBVR, Gunn i, and Hα with the 2.2m's standard filter set.

We observed several UBV(RI)$_{\rm C}$ standard fields from Landolt (1992) on 08 Oct 1993 resulting in a total of 47 standard star observations. The data were reduced using the standard procedures in DAOPHOT II running under MIDAS (Stetson 1992). We then used own programs that correctly remove atmospheric extinction effects (Roberts & Grebel 1995) and transform to the UBV(RI)$_{\rm C}$ standard system (Roberts 1996).

Outside a radius of 22 pc around the cluster center the number of stars normalized by area is constant. We therefore consider stars outside this radius to be mainly field stars. In Fig. 1, only stars within 22 pc around the cluster are plotted. Our best-fitting isochrone is indicated by a solid line. For more details on the isochrone fitting procedure see Roberts (1996) and Grebel et al. (1994a). Fig. 1b in Grebel et al. (1994b) shows the full frame for NGC 330 and the surrounding field. In both diagrams, several stars are visible above the main-sequence turnoff and below the supergiant locus. The main-sequence turnoff as given by the isochrone is at $V \approx 15.6$. Inevitably, the resulting magnitude difference between the loci of the blue supergiants and the main sequence is $\Delta V \approx -2.5$ mag, which is expected from theory and is independent from the set of opacities and the amount of overshoot used (Stothers & Chin 1992).

Note that our isochrone fits the location of the blue and red supergiants. In past studies, the stars above the main-sequence turnoff defined by our isochrone have either been considered ordinary main-sequence stars whose tip indicates the main-sequence turnoff (Carney et al. 1985) or as main-sequence stars younger than the rest of the cluster, thus indicating an age spread. Possible age spreads of 10 Myr for Geneva models (Bomans & Grebel 1994), 15 Myr for semiconvective Padua models, and as much as 38 Myr for models with full overshoot (Chiosi et al. 1995) have been suggested. However, when fitting the position of the stars above our isochrone turnoff to younger isochrones there are no supergiants at the positions corresponding to the supergiant loci of these isochrones. This might be an effect of small-number statistics, though on the other hand it seems strange that the supposedly ongoing star formation would not have resulted in the evolution of additional, younger supergiants. Obviously, additional data are needed.

3. The spectroscopic data

3.1. The observations

Our spectroscopic data were obtained with a Boller & Chivens spectrograph attached to the ESO 1.52m telescope on 29 Dec 1993 and on 28 July 1994. The B&C spectrograph was equipped with a UV coated 2048×2048 Ford chip (ESO # 24). The angular pixel scale was $0\farcs81$/pixel. We used grating # 23, covering a wavelength range from 390 to 780 nm in the first observing run and 370 to 730 nm in the second run. The

Table 1. Determinations of spectral types for a number of blue stars found above the main-sequence turnoff. The column names have the following meaning: "Arp" stands for the naming convention introduced for bright stars in NGC 330 by Arp (1959) on his plates I and II. "Rob" denotes the naming convention used by Robertson (1974). "FB" gives the spectral classifications summarized in the paper by Feast & Black (1980), "CJF" lists the classifications of Carney et al. (1985), and "LMPBC" comprises the classifications carried out by Lennon et al. (1995). "Above MS" indicates by "y" for yes and "n" for no whether stars lie above or below the main-sequence (MS) turnoff defined by our best-fitting isochrone. "LDMPM" refers to radial velocities from Lennon et al. (1996). The rest is self-explanatory. Radial velocities in the range from 140 to 155 km s^{-1} indicate likely members of NGC 330.

star ID		spectral classification						above	v_{rad} [km s^{-1}]		
Arp	Rob	FB	CJF	LMPBC	this study	V [mag]	B–V [mag]	MS?	FB	CJF	LDMPM
II-13	A1			B0.5 III/Ve	B0-1 III	14.81 ± 0.05	-0.19 ± 0.10	y	145		153 ± 6
II-14	A2	B5 I	B6 I	B4 Ib	B5 I	13.33 ± 0.05	-0.30 ± 0.06	y	139 ± 2	147 ± 16	
II-31	A4				B2-3 IIe	14.54 ± 0.02	-0.00 ± 0.03	y	144		
II-16	A16	B9 I	A2 I			13.14 ± 0.05	$+0.06 \pm 0.06$	y	148 ± 5	154 ± 8	
II-33	A25	A1 I	A0 I			13.09 ± 0.02	$+0.09 \pm 0.03$	y	149 ± 2	155 ± 11	
II-40	A29	B9 I				13.12 ± 0.02	$+0.12 \pm 0.02$	y	139 ± 5		
II-35	A47	B9 I				12.64 ± 0.02	$+0.06 \pm 0.04$	y	145 ± 1		
I-243	B2		A7 I			13.80 ± 0.10	$+0.09 \pm 0.11$	y		111 ± 17	
I-235	B4			B2 IIIe		16.21 ± 0.12	-0.58 ± 0.13	n			150 ± 4
I-234	B5			B2 IIIe		15.61 ± 0.13	-0.03 ± 0.14	n			
I-233	B6			B2 IIIe		15.59 ± 0.11	-0.02 ± 0.12	n			
I-232	B7			B2 IIIe		15.18 ± 0.18	-0.75 ± 0.18	n			
I-223	B11			A0 II		15.61 ± 0.09	-0.01 ± 0.15	n			
I-47	B12			B2 IIIe		15.43 ± 0.08	-0.05 ± 0.09	y	154		
II-28	B13			B2 III/IVe		15.80 ± 0.03	-0.15 ± 0.05	n	138		
I-222	B16		A0 I	A0 II	B9/A0 Ib	13.92 ± 0.01	$+0.08 \pm 0.02$	y			
I-204	B18			O9 III/Ve		15.74 ± 0.02	-0.19 ± 0.03	n			
II-46	B21		B4e,n	B2.5 IIe		14.41 ± 0.02	$+0.10 \pm 0.03$	y		113 ± 19	
II-45	B22			B2 IIe	B3 II	14.33 ± 0.02	-0.09 ± 0.03	y	149 ± 4	149 ± 9	
I-f	B24			B2 IIIe	B1 IVe	15.24 ± 0.05	-0.12 ± 0.08	y			
	B28			B0.2 IIIe		15.73 ± 0.02	-0.19 ± 0.09	n			
II-1	B29	A0 I	A1 I			13.42 ± 0.03	$+0.05 \pm 0.08$	y	127 ± 5	122 ± 12	
II-3	B30		B6 I	B2 II	B1 II	14.30 ± 0.02	-0.14 ± 0.04	y	140 ± 4	148 ± 15	
II-4	B33				B2-3 Ve	15.88 ± 0.02	-0.16 ± 0.05	n			
	B35			B2 IIIe		15.38 ± 0.06	-0.09 ± 0.16	y			
II-8	B37	B5 I	B5 I	B3 Ib		13.29 ± 0.05	-0.07 ± 0.08	y	148 ± 5	127 ± 26	
II-9	B38	A1 I	A5 I			13.47 ± 0.10	-0.47 ± 0.13	y	151 ± 1	133 ± 14	
I-c					B8 II	14.09 ± 0.05	$+0.18 \pm 0.07$	y			
I-201			A1 I			13.32 ± 0.02	$+0.14 \pm 0.06$	y		103 ± 8	
I-206					B9 II	14.26 ± 0.01	$+0.03 \pm 0.02$	y			
I-207					B8 III	14.74 ± 0.03	$+0.12 \pm 0.05$	y			
I-211			A0 I			13.81 ± 0.01	$+0.04 \pm 0.05$	y		99 ± 6	
I-218					B1 V	15.64 ± 0.23	-0.29 ± 0.24	n			
I-219					B9/A0 III	14.66 ± 0.07	-0.09 ± 0.08	y			
I-220					B3 III-IV	15.16 ± 0.27	$+0.52 \pm 0.35$	y			

slit width was $2''$. With 0.19 nm/pixel, we obtained a resolution of ≈ 1000 in the blue. An order separation filter (WG 360) with a cutoff at 360 nm was used to prevent second order overlap.

The orientable slit allowed us to observe two target stars simultaneously. Because of the wide slit we often obtained spectra of other stars as well in one exposure. Of course we did not get all the light from the other stars since some of them would be positioned on the edge of the slit. Additional light loss occurred due to guiding errors (an autoguider was not yet available at the 1.52m telescope) and refractory losses at higher airmasses. Therefore no flux calibration was attempted, though we observed two spectrophotometric standards per night to determine the response curve of the instrument. The FWHM of the PSF in spatial direction varied between $1\farcs8$ and $2\farcs8$. In total we observed 20 stars located in the outer regions of the cluster (not all of them blue). All spectra had exposure times of 30 min (except for one exposure of 25 min).

3.2. Reduction and analysis

The raw data were reduced in the standard way, i.e., bias subtracted and flatfielded by a normalized dome flat in order to remove pixel-to-pixel variations. The individual spectra were extracted, sky-subtracted, and wavelength-calibrated using the dispersion relation from the He–Ar comparison spectra. For the extinction correction the standard La Silla extinction curve as incorporated into MIDAS was used. An instrumental response curve was derived in the same way from the standard stars. Then the target stars were response-corrected with this curve and rectified.

The poor signal-to-noise ratio in the violet made it difficult to determine spectral types for the spectra from Dec 93. Therefore the data from Jul 94 were used whenever possible. For our spectral classifications we used digital versions of the OB star atlas of Walborn & Fitzpatrick (1990) and the spectral atlas by Jacoby et al. (1984).

4. Spectroscopic results from our and other studies

4.1. Spectral classifications

Fig. 2 shows our spectra with line identifications and classifications. Additional spectral classifications were performed by Feast & Black (1980), Carney et al. (1985), and Lennon et al. (1994, 1995). Combining all these data, we find that the majority of blue stars with $15.6 \leq$ V ≤ 14.0 mag belong to luminosity class IV, III, and II, while stars brighter than V ≈ 14 mag are supergiants (Tab. 1). We shall refer to the stars of luminosity class IV, III, and II in the following as *blue giants*. The two spectroscopically classified main-sequence stars lie below the main-sequence turnoff indicated by our isochrones. Thus the main-sequence turnoff determined from our isochrone fits agrees well with the position of stars identified spectroscopically as main-sequence stars, as well as with that of the blue and red supergiants.

The supergiants are mostly intermediate- and late-type B supergiants and early A-type supergiants. The blue giants span the entire B-type range. The two B main-sequence stars in our sample are early B-type stars (B1 V to B2 V), which is not surprising since only spectra of the brightest blue stars were taken. For a discussion of individual stars, see Sect. 4.3. The majority of the stars show Hα emission. Spectral types determined by different authors vary within a few subtypes, which may be due to different recording techniques (e.g., resolution, and CCD frames versus image tube spectra) and analytical techniques. Also, spectral classifications are difficult in the metal-poor SMC due to the fewer/weaker metal lines than in luminous blue Galactic stars (Walborn et al. 1995, Lennon et al. 1995). The spectra with the highest resolution and best S/N for B stars in NGC 330 are those obtained by Lennon et al. (1994).

4.2. Determinations of effective temperatures and surface gravities

Reitermann et al. (1990) analyzed high-resolution echelle spectra in the visual and low-resolution IUE spectra of the B star B30 (naming convention from Robertson 1974) in NGC 330. In their H-R diagram, B30 lies in the post main-sequence gap. Reitermann et al. suggest that this star has not yet been a red supergiant. Bessell (1991) determined surface gravities for B22, B30, and B37 in NGC 330. In both studies, low surface gravities were found (Tab. 2).

Reitermann et al. (1990) nicely illustrate in their Fig. 2 the uncertainties in determinations of effective temperatures and surface gravities when comparing the results from different methods, namely those based on the "reddening-free index" Q = $(U-B) - 0.72{\cdot}(B-V)$, the equivalent width of Balmer lines, and the SIII/SII ionization equilibrium. Often $T_{\rm eff}$ values are based on Q alone and very susceptible to the effects of individual reddenings and colour excesses. Transformation equations for determination of $T_{\rm eff}$ as given in Massey et al. (1995) furthermore require advance knowledge of the luminosity class.

However, since the analyses by different authors, which are in part based on different data and different methods, agree quite well within the errors, we believe that the location of the blue giants in the blue Hertzsprung gap is not caused by erroneous transformations.

Caloi et al. (1993) analyzed IUE spectra of many of the stars below the blue supergiant locus and used Kurucz models to determine temperatures and surface gravities (Tab. 2). Though they could not determine spectral types, they found temperatures and surface gravities of these stars as well as their position in the post main-sequence gap of the H-R diagram incompatible with their being main-sequence stars. They pointed out problems in interpreting the evolutionary status of these stars, a finding that was confirmed by Lennon et al. (1994). Lennon et al. determined temperatures and surface gravities from fits of LTE and non-LTE model atmospheres and Robertson's (1974) BV photometry.

4.3. Results for individual stars

Caloi et al. (1993) find the stars B4, B5, B6, B21, B22, and B30 to lie on the subgiant branch in their theoretical H-R diagram. These are statistically too many stars for a phase traversed so quickly. They mention that B4 because of its low temperature resembles an evolved star, which would mean an age spread of 15 Myr. Masses of these apparently evolved stars seem to be of the order of 10 $M_\odot$, which would indicate that mass loss is a lot less efficient than usually assumed. In Jüttner's (1993) H-R diagram star B22 lies very close to the TAMS, while B30 lies in the post main-sequence gap. Jüttner derives a mass of ≈ 10 $M_\odot$ for B30 and ≈ 15 $M_\odot$ for B22.

Lennon et al. (1994) suggest that some of the supergiants (A2, B37) and bright giants (B21, B22, B30) with redder colours may be evolved post red supergiants, while A1 and B18

Table 2. Determinations of surface gravities, effective temperatures, and masses for blue stars found above the main-sequence turnoff and below the young blue supergiants. All stars are identified by the denotations introduced by Robertson (1974). "RBSW" quotes values from Reitermann et al. (1990). The column "Bessell" gives his measurements from 1991. "Jüttner" gives Jüttner's values (1993), "CCCW" stands for Caloi et al. (1993), and "LMPBC"gives the results of Lennon et al. (1994), which were replaced by the revised values of Mazzali et al. (1995) when available. The errors of the $\log g$ determinations range from 0.1 to 0.5. The errors of the temperature determinations are between 1000 and 5000 K. Column "Be" indicates whether the star was found to show Hα emission (Grebel et al. 1992, 1994b, Lennon et al. 1994). The stars A2 and B37 are supergiants. Stars identified as variables by Balona ("Ba", 1992) or by Sebo & Wood ("SW", 1994) are listed in the last column.

Star ID	RBSW		Bessell	Jüttner		CCCW		LMPBC/MLPMC			Ba/SW
	$\log g$	$T_{\rm eff}$	$\log g$	$\log g$	$T_{\rm eff}$	$\log g$	$T_{\rm eff}$	$\log g$	$T_{\rm eff}$	Be	variable
A01						3.7	28,000	4.10	28,000	y	
A02						2.5	15,000	2.50	16,000	n	
B04						3.9	23,000	3.80	25,000	y	
B05						3.7	19,000	3.50	22,000	y	Ba964,λEri
B06						3.7	22,000	3.40	22,000	y	
B07								3.80	24,000	y	
B11								3.25	12,000	n	
B12								3.50	23,000	y	
B13								3.60	22,000	y	
B18								4.50	32,000	y	
B21						3.4	22,000	2.80	20,000	y	
B22			3.2	3.22	22,700	3.2	20,000	3.25	21,000	y	
B24								3.80	25,000	y	HV1669
B28								4.50	30,000	y	
B30	3.00	18,700	3.1	2.91	18,800	3.2	19,000	3.25	21,000	n	
B32						3.8	28,000			?	Ba347,λEri
B35								3.50	25,000	y	
B37			2.8			2.7	17,000	2.60	18,000	n	

(both bright, but bluer and higher $\log g$) could be blue stragglers. We are here using the notations introduced by Robertson (1974) when referring to these stars. Star B18 was re-classified as an O9 giant or main-sequence star (Lennon et al., 1995). In our Hα frames, this star is the brightest star at the center of a large, elliptical HII region of about $1'$ in diameter, part of DEMS 87 (Davies et al. 1976), located approximately $1\farcm3$ northwest of NGC 330. B18 may be (one of) the exciting star(s) of the HII region, in which case it is probably not a member of NGC 330. This suggestion is circumstantially supported also by the fact that B18 is outside the membership radius described in Sect. 2. The comparatively low V magnitude (for a late O star) may be due to higher extinction in the HII region, which then would amount to a few tenths of a magnitude. It is possible that B18 is more heavily extincted than other stars in this region because this O star appears a little fainter than the brightest early B main-sequence stars.

Lennon et al. (1994) find the bright giants or supergiants B11 and B16 to be very red and suggest that these stars might be SMC field stars. In our data the supergiant B16 is quite red as well and, in our photometry, shows Hα emission, while B11 does not have red colours and photometrically appears to be a main-sequence star. A number of stars classified as B giants and subgiants by Lennon et al. (1995) or by us lie in the main-sequence turnoff region, partly even a little below (Tab. 1). Of these stars, B4, B5, B6, B12, B13, and B28 were found to show Hα emission and are Be stars (Grebel et al. 1992, 1994b, Lennon et al. 1994, Grebel 1995, Mazzali et al. 1995). We classify star B33 as a main-sequence Be star below the main-sequence turnoff. The more distant (and probable non-member) star I-218 is a main-sequence star without Balmer emission. Judging from their $\log g$ values, B28 and B18 may also qualify as a main-sequence stars. Many stars above the turnoff are Be stars (e.g., A1, A4, A15, A22, A39, B7, B12, B17, B21, B22, B24, B35, Tab. 1, Grebel 1995), some of which were identified as λ Eri variables or eclipsing binaries (Balona 1992, Sebo & Wood 1994, Grebel 1995).

Chiosi et al. (1995) plot the stars of Caloi et al. (1993) in an H-R diagram together with main-sequence and blue-loop boundaries for different types of evolutionary models. They find that when using models with full overshoot, which considerably widens the main sequence and shifts the TAMS to the red, all stars are located within the permissible boundaries of the TAMS except for B21, B22, and B30, which still lie in the post main-sequence gap.

There are a number of stars above the main-sequence turnoff that do not show Balmer emission, or did not show Balmer emission at the times they were observed. Some of these stars tend to have as blue colours as the main-sequence stars beneath them, while the Be stars generally stand out

through their red excess in the redder colour indices, as one would expect.

We also note a decline in number density of stars above the main-sequence turnoff as determined spectroscopically and by isochrone fitting. This decline can be seen clearly in the $B-R$ and $V-I$ CMDs (Fig. 1).

We shall now discuss the possible evolutionary status and nature of those unexpected blue stars above the main sequence and below the area of the blue supergiants in NGC 330. There are two possibilities: (1) evolved giants or (2) core H burning main-sequence stars.

5. Blue giants = evolved stars?

We have to consider that the blue giants in NGC 330 may be evolved stars. As mentioned already, to find any stars in the subgiant region of the H-R diagram at all is unlikely because evolution here proceeds rapidly (e.g., Langer & Maeder 1995), and to find so many is statistically nearly impossible according to current evolutionary models. It can be excluded that all of these stars are subgiants.

5.1. Evolved field stars

Of course NGC 330 is heavily contaminated by the surrounding young field population. Our blue giants might simply be older, evolved field stars that we see superimposed on the cluster. However, the number-density distribution of blue giants is concentrated toward the cluster, and several of the blue giants are radial velocity members of NGC 330. We estimate that stars in the velocity range of 140 to 155 km s^{-1} belong to NGC 330 (Tab. 1) following the measurements of Feast & Black (1980), Carney et al. (1985), and Lennon et al. (1996), which make A1, A4, A16, A29, A47, B4, B12, B22, and B30 radial velocity members. Potential additional members with radial velocities at the lower end of the distribution are A2, A29, and B13. We therefore exclude that the blue giants are merely evolved field stars seen in superposition.

Radial velocity measurements for B37 and B38 by Feast & Black (1980) support their being members of NGC 330, while Carney et al.'s (1985) results would make them field stars. The stars B2, B21, B29, I-201, and I-211, all of which are supergiants except for B21, are probably not members of NGC 330 (which is further supported by their distances from the cluster).

5.2. Post-red supergiants

While the positions of the supergiants A2 and B37 in the H-R diagram (Caloi et al. 1993, Lennon et al. 1994) agree with Lennon et al.'s suggestion that they are He burning, evolved post-red supergiants, the blue loops of the Geneva models do not reach far enough to the blue for the bright giants B21, B22, and B30. Missing opacity could account for missing blue loops for less massive stars (Stothers & Chin 1994).

The atmospheric composition of post-red supergiants should have changed due to admixture of CNO-cycle products (Walborn 1988), so high-resolution spectroscopic analyses should be able to clarify their evolutionary status. The Ledoux criterion plus semiconvection work well for low-metallicity stars (Stothers & Chin 1994), though adoption of the Ledoux criterion has little effect on stars in their main-sequence phase (Stothers & Chin 1992). However, for metal-poor red supergiants the Ledoux criterion will lead to normal C/N ratios because of shallow convection envelopes. The same holds for the blue supergiant phase. Thus alteration of surface composition is not necessarily to be expected.

Fitzpatrick (1991) found a large spread in N equivalent widths among B-type supergiants in the LMC, and Fitzpatrick & Bohannan (1993) suggest that 10 to 20% of the stars in their sample are pre-red supergiants. For some Galactic blue supergiants it has been suggested that they suffered partial mixing of CN-cycled gas near the main sequence (Gies & Lambert 1992, Lennon 1994, Venn 1995), i.e., these stars, too, show CNO abundances different from unevolved B main-sequence stars.

High-resolution spectroscopy of blue supergiants in the Magellanic Clouds generally showed significant He and N enrichment, while C and O were depleted (Kudritzki et al. 1987, Lennon et al. 1991, Humphreys et al. 1991, Fitzpatrick & Bohannan 1993, Walborn et al. 1995), which has been attributed to these stars being post-red supergiants. This indicates that even in metal-poor environments such as in the Magellanic Clouds the surface composition changes in general when evolving through the supergiant phase.

As Caloi et al. (1993) point out, high-resolution studies of B30 in NGC 330 do not show He or N enrichment (Reitermann et al. 1990). The same was found for B22 (Jüttner et al. 1993, Tab. 3). It therefore does not seem very likely that these blue giants are post-red supergiants.

In a high-resolution study of the narrow-line Be stars A1 and B4, Lennon et al. (1996) find these stars highly enriched in nitrogen, while no helium enrichment and no carbon deficiency is observed as would be expected from supergiant evolution (Tab. 3).

5.3. Schwarzschild convection & Case-B evolution?

When the Schwarzschild criterion for convection is used, a main-sequence star can evolve after core H exhaustion to become a blue supergiant before having passed through the red-supergiant phase (Case-B evolution, Chiosi & Summa 1970 and discussion in Fitzpatrick & Garmany 1990). A star of 15 $M_\odot$ would be a Case-B blue supergiant at an age of about 11 Myr following the evolutionary calculations for Case-B by Brunish & Truran (1982).

A comparison of Brunish & Truran's Fig. 3 and the H-R diagram given by Caloi et al. (1993) and Lennon et al. (1994) shows that the location of the "blue giants" is compatible with the position of blue supergiants in Brunish & Truran's models. However, if we consider the blue giants to have evolved in the sense of Brunish & Truran, we face the problem of how to explain the presence and location of the "normal" supergiants,

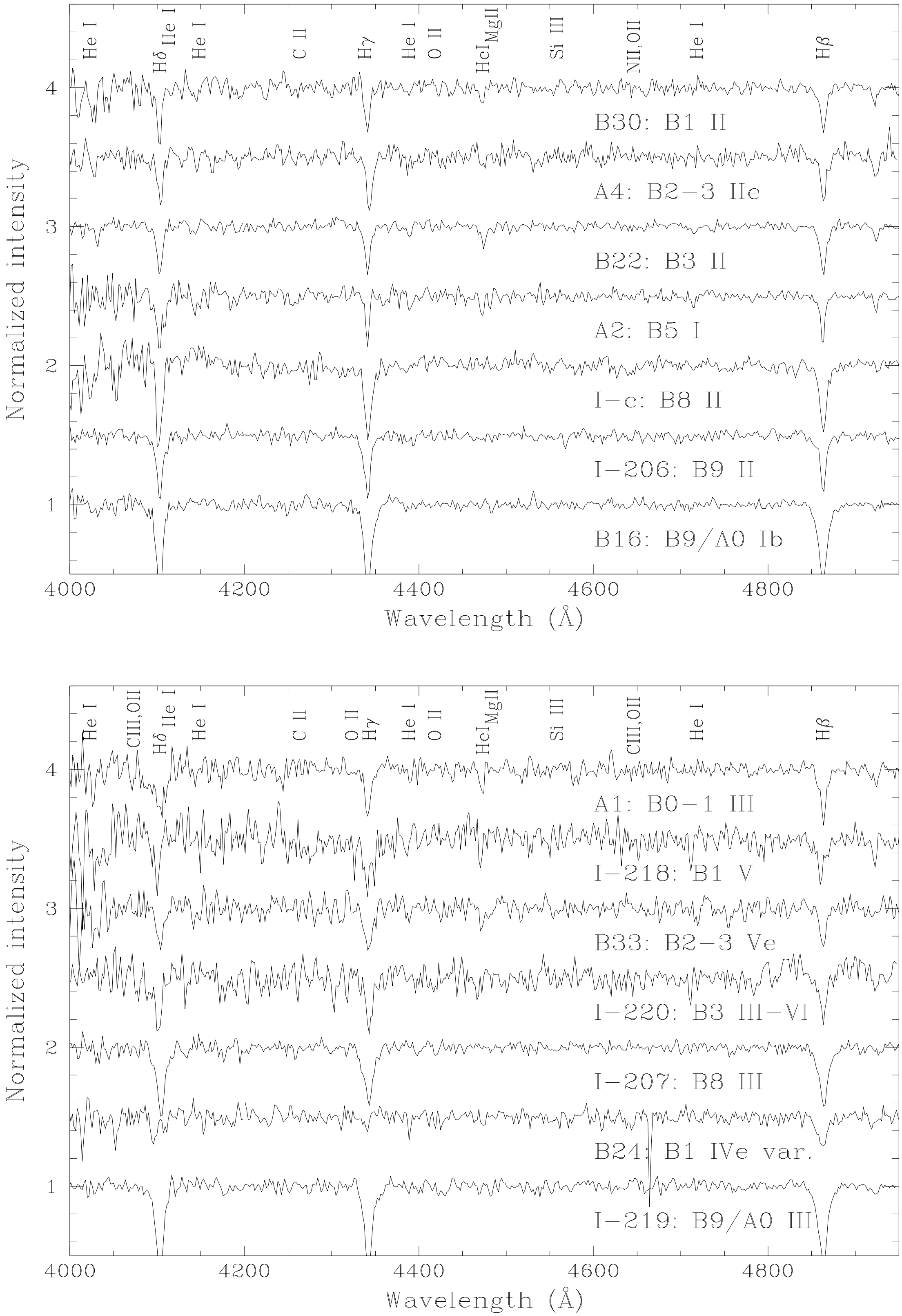

Fig. 2. The upper panel contains spectra of supergiants and bright giants in NGC 330. In the lower panel, spectra of giants and main-sequence stars in NGC 330 are displayed.

both blue and red. Besides, we found NGC 330 to be about twice as old as the above-quoted model from fits to Geneva isochrones, which of course are based on different model parameters such as a certain amount of convective core overshooting leading to higher ages, a different metallicity, and current opacity models. If we were to assume an age spread to explain the presence of such massive Case-B B supergiants, we would again be confronted with the problem of explaining why within one cluster two different types of stellar evolution and convection could take place. It does not seem likely that the Case-B scenario is at work in NGC 330.

5.4. Dependence of derived $\log g$ and $T_{\rm eff}$ on rotation

The effects of rapid rotation may change the inferred spectral classification (Slettebak et al. 1980). As Collins (1987) points out, deviations from spherical symmetry caused by rapid rotation imply that there is no longer a global $T_{\rm eff}$ and $\log g$. Instead, one can only determine a specific $T_{\rm eff}$ and a specific $\log g$ that is valid for the observed inclination angle. Both quantities vary across the stellar surface depending on co-latitude. From pole-on inclinations to equator-on, the spectroscopic gravity may differ by a factor of ten, and the photometrically derived effective temperature may vary by several thousand degrees (see Collins's (1987) Fig. 2, see also Slettebak et al. 1980). This should be kept in mind when looking at the $T_{\rm eff}$ and $\log g$ values listed in Tab. 2. If rapid rotation plays a rôle here, then these values do not necessarily imply that these stars are evolved. The effects of rotation will be discussed in detail in the next section.

6. Blue giants = main-sequence stars?

6.1. Ordinary main-sequence stars

Luminous core H burning main-sequence stars may spectroscopically appear as giants, as has long been known (e.g., Massey et al. 1995 and references therein). However, ordinary core H burning stars would not be found in the blue Hertzsprung gap of the H-R diagram. Also the sudden decline in number density above the main-sequence turnoff indicates that the blue giants may be different from main-sequence stars.

For the blue giants to be ordinary main-sequence stars, the main sequence needs to be a lot wider than given by the models of the Geneva group – so wide that it covers that part of the blue Hertzsprung gap in which the blue giants are found. Following the suggestion by Tuchman & Wheeler (1990), Chiosi et al. (1995) demonstrate that this can partially be achieved by full overshoot models, for which several but not all of the blue giants in NGC 330 lie close to the TAMS, while the blue Hertzsprung gap and the blue supergiant loop are shifted further to the red. Full overshoot is, though, an extreme hypothesis that does not fit well with modern mixing length theories (e.g., Grossman et al. 1993). Both the Padua group and the Geneva group have meanwhile adopted a moderate amount of overshoot that seems to fit observations in the Milky Way and in the Magellanic Clouds best. Thus, our blue giants do not seem to be ordinary main-sequence stars in the sense previously defined.

Bessell & Wood (1993) pointed out that the location of the blue giants at lower effective temperatures could also be reproduced when using the evolutionary tracks of Doom (1985). These models use the Roxburgh criterion for convection and overshoot, are more centrally concentrated, and reach higher luminosities and lower effective temperatures. The location of the TAMS is in agreement with the location of the blue giants. Spin-up, proposed by Bessell & Wood as a possible cause for the Be phenomenon due to rotationally induced mass loss, is fostered by these models. These models might be a valid explanation for what we observe. However, if with anticipation of the discussion in later sections we take into account that each cluster has a certain fraction of binary stars, in the models of Doom these stars would have to appear shifted even further to the red, and as we shall see later, that does not agree with what is observed in Galactic open clusters with binaries (s. Pols & Marinus 1994).

6.2. Rapid rotators

Models taking into account high rotational velocities may also be able to account for (part of) the blue giants. Many of the blue giants are Be stars, thus supposedly rapid rotators. We will discuss the implications of the presence of Be stars below.

Rotational effects were studied by Collins & Smith (1985, s. also Maeder & Peytremann 1970, 1972) and Collins et al. (1991)), who show that the amount of main-sequence widening depends, apart from rotational velocities, on whether stars rotate as rigid bodies or differentially. The stronger the differential rotation, the wider the main sequence. The main sequence of differentially-rotating stars broadens particularly for stars of later types (A,F), while the effects are less pronounced in the steep part described by B-type stars.

As Collins et al. (1991) have shown, the observed brightness of a B star is (among other things) a function of its rotational velocity and its inclination to the line of sight. A pole-on rotator (inclination angle $i < 30^\circ$) is displaced upwards from the main sequence of "non"-rotating stars and will be much (up to a magnitude) brighter than other B stars of the same spectral type but at different inclination angles. The larger the inclination angle (maximum 90°, equator-on; common definition for equator-on: $i > 60^\circ$, Collins 1987) of a B star toward us, the redder the star becomes, and, though still brighter than a non-rotating star, less luminous. Therefore, a star with a given, high rotational speed describes what Collins et al. (1991) call the "rotational displacement fan" in a colour-magnitude diagram (s. their Fig. 1), its actual colour and brightness depending on its inclination angle.

As Collins et al. explain, rotational distortion causes a pole-on rotator to present a larger surface area including the high-temperature polar regions free of limb darkening and gravity darkening. Therefore such a star appears brighter than a non-rotating star seen pole-on. Rapidly rotating stars seen equator-on exhibit very strong limb darkening in their polar regions and,

through rotational distortion, have more extended, cooler equatorial regions than non-rotating stars. Both effects make them fainter than non-rotating counterparts. The latter also causes them to appear redder.

Rapid rotation also influences the interior of the rotating star, in essence causing a lower surface temperature, and stars may appear even more shifted to redder colours than in models considering only rotational distortion-induced changes in the atmosphere.

The positions of the Be stars in NGC 330, which mostly are redward of the main sequence in our CMDs (Figs. 1), may to a large extent be caused by rotational displacement as just explained. Stothers & Chin (1992) suggest that either strong convective envelope overshoot or fast interior rotation may account for the H-R diagram of NGC 330 and point out the high fraction of presumably rapidly rotating Be stars in NGC 330. For most of the stars without Balmer emission and vertically above the main sequence their height above the main sequence is in accordance with what one might expect for pole-on rotators. More about that in the next section.

6.3. Be stars?

Most of the blue giants have been identified as Be stars (Grebel et al. 1992, 1994b, Lennon et al. 1994, Grebel 1995, Tab. 2 and 1). As already mentioned, not all of the blue giants currently show Hα emission, but the Be phenomenon is known to be variable and episodic.

Most (Galactic) Be stars are rapid rotators (Slettebak 1988). The effects of rotational distortion were just explained in the preceding section. Be stars in addition often show an infrared excess due to free-free emission in their disks, which already becomes visible in red filters of the visual wavelength range (Fig. 1).

The position of the majority of the blue giants in the H-R diagram can be explained by their being Be stars and thus shifted to lower effective temperatures and lower surface gravities due to effects of rotation and (infra-)red excess.

Since NGC 330 is unusually rich in Be stars (Grebel et al. 1992, 1994b), we will now discuss the hypothesis that all blue giants in NGC 330 are Be stars, even though some do not show Balmer emission at the moment. If all blue giants were Be stars, this would imply that the stars vertically above the main sequence must be pole-on rotators. We assume that the rotational axes of these stars would have to be within about 30° of the line of sight so that limb darkening and the small solid angle of the equatorial regions would make the stars significantly brighter and bluer (and smaller angles would be significantly more effective). The solid angle within 30° of *both* poles is about $2 \cdot 2\pi \cdot (1 - cos(30^\circ)) = 4\pi \cdot 0.134$, so the probability of a Be star's having such an orientation is roughly 1 in 8. In our CMDs of NGC 330, we see nine blue giants that lie more or less vertically above the main sequence. If these are pole-on rotators, we expect approximately 63 non-pole-on Be stars. Rapid rotation may affect both B and Be stars. Furthermore, it has to be considered that pole-on rotators will not only be present above the main sequence, but also along the main sequence just as the Be stars span a range of magnitudes. Also, for our comparison of pole-on and non-pole-on rotators to be meaningful we must confine ourselves to stars only within the magnitude range that may give rise to the observed nine vertically displaced blue giants. Thus we need to count B stars and Be stars within one magnitude below the main-sequence turnoff (and the Be stars above it) to establish a valid base of comparison. The number ratio is approximately 60 supposedly non-pole-on B and Be stars versus nine possible pole-on rotators above the main sequence. (At this point, we note again that these nine stars above the main sequence do not show Hα emission.) Considering the uncertainties of the numbers, incompleteness, and crowding, we cannot rule out that those nine blue giants are pole-on rotators.

Statistically, the only possibility for all blue giants in NGC 330 with or without current Hα emission to be Be stars is that *all* B stars in NGC 330 would have to undergo the Be star phenomenon at some point of their evolution. If all bright B stars are rapid rotators this would suffice to explain the presence of the vertically displaced blue giants. As rapid rotators and/or Be stars, the blue giants may well still be core H burning.

It is not yet known if the B-type stars in NGC 330 are rapid rotators. Lennon et al. (1994) and Mazzali et al. (1995) determined rotational velocities for a large number of Be stars in NGC 330. However, these measurements are based on the Hα emission line, which originates in the circumstellar disk around the Be stars and may not be representative for the rotational velocity of these stars. Reitermann (1989) determined $v \sin i$ values for seven B type stars in NGC 330. The $v \sin i$ values range from 45 km s^{-1} to > 100 km s^{-1}. Since the inclination angles are not known, we do not know what the rotational velocities are. At the current time, it cannot yet be verified whether or not B-type stars in NGC 330 are rapid rotators. Based on fitting their models, Stothers & Chin (1992) suggest that stars in NGC 330 suffer fast interior rotation. Balona (1992) estimates from the mean periods and magnitudes of the 19 λ Eri variables that he found in NGC 330 that the mean equatorial rotational velocity of these stars may be 375 km s^{-1}, a relatively high value as compared to Galactic λ Eri variables. Fast rotation may facilitate the formation of Be stars and short-periodic Be variables such as λ Eri stars.

We point out in this context that NGC 1818 and NGC 2004, two young clusters in the LMC that also seem to contain blue giants, have comparatively many fewer Be stars (Grebel et al. 1994b, Sect. 7).

6.4. Blue stragglers and binary stars

Those blue giants vertically above the main sequence could also be blue stragglers. By definition, blue stragglers are stars that appear to have "straggled" in their main-sequence evolution and, while still being core H burning main-sequence stars, lie above the main-sequence turnoff given by the age of the cluster in question (Stryker 1993). Blue stragglers have been

found in all kinds of stellar aggregates, from old globular clusters down to young OB associations (Mermilliod 1992).

Blue stragglers may be the result of delayed formation (star formation over an extended period of time) or of delayed evolution (binaries with mass transfer, Eggen & Iben 1988). In the first case, the blue stragglers are likely to be single stars. Should the blue giants found vertically above the main sequence be the result of delayed formation, we would expect them to show spectral characteristics typical for earlier types of stars. In the case of NGC 330, where the earliest stars on the main sequence found from isochrone-fitting are of type B0 to B1, we would consequently expect the most massive younger stars to be O stars. This however is not what we observe.

Thus the delayed-evolution scenario appears to be more likely. In fact there is mounting evidence that blue stragglers result from binary interactions (Stryker 1993).

Collier & Jenkins (1984) present model calculations for Case-B mass transfer, i.e., mass transfer through Roche-lobe overflow while the primary component is already a red giant. To quote, the "two most notable features resulting from the inclusion of the binary population are the splitting of the main sequence, and the presence of a sequence of blue stars near the main sequence but *above* the cluster turn-off." (Collier & Jenkins 1984). This effect is visible in our CMDs and even more pronounced in NGC 1818 (Will et al. 1995).

As Collier & Jenkins point out, for stars with primaries more massive than 2.5 $M_{\odot}$, Case-A mass transfer is more prevalent than Case B. In Case-A evolution, the system is so close that Roche-lobe overflow occurs already on the main sequence (Kippenhahn & Weigert 1967). Following Kippenhahn's & Weigert's model calculations, the age of NGC 330 is compatible with its containing very massive secondaries (mass $> 11\ M_{\odot}$) that would appear as blue stragglers. The binary system in this case looks like a semi-detached Algol-type system, where the less massive component fills its Roche lobe and appears as overluminous subgiant. On the other hand, de Loore & Vanbeveren (1994) argue that with decreasing metallicity, the importance of Case-A mass transfer decreases as well.

Tuchman & Wheeler (1990) present a scenario in which the Hertzsprung gap can be filled if a main-sequence star gets enriched in He by a more massive red-supergiant companion through Roche-lobe overflow. The main-sequence star becomes a peculiar blue giant while the more massive companion may become a supernova or a neutron star.

As mentioned before, though, high-resolution studies of two bright giants in NGC 330 (Reitermann et al. 1990, Jüttner et al. 1993) did not find evidence for He enrichment, nor for N enrichment (compare with Jüttner et al.'s results for field stars, Tab. 3). That would seem to exclude the possibility that we are seeing the effects of homogeneous evolution of massive stars leading to the formation of OBN blue stragglers (Maeder 1987, Beech & Mihalas 1989). These two stars with their very low surface gravities may, however, be coalesced binaries or a similar result of massive close binary evolution. On the other hand, Lennon et al.'s (1996) finding of significant N enrichment in A1 and B4 without the accompanying C and O depletion (compare to the results of Rolleston et al. 1993, who used the same method; Tab. 3). The authors suggest binary mass transfer or rotationally induced mixing for these two stars with low v sin i values. They might be pole-on rotators, but a number of discrepancies are yet to be solved. For discussions, see Luck & Lambert (1992) and Lennon et al. (1996).

Pols (1994) presents detailed results for Case-A and Case-B mass transfer between massive close binaries. It is likely that these interactions result in one of the components becoming a (comparatively low-mass) He star, which then would appear blueward of the ordinary core H burning main sequence (blue interloper). While we see some fainter stars displaced to the blue of the hydrogen main sequence, these stars may simply be there because of large photometric errors and scatter for fainter magnitudes. Spectroscopy of these stars would be useful.

Studying the short-periodic variability of stars in NGC 330, Balona (1992) found three early-type eclipsing binaries, one of them probably a contact system. In a study of long-periodic variability of stars in the surroundings of NGC 330, Sebo & Wood (1994) found one eclipsing binary in the region of the blue giants (HV 1669 or B24, a B1 IVe star, s. Tab. 2) and three other binaries, one of them a contact W UMa-type star. Of these, HV11348 was identified as Be star (Grebel 1995, suspected already by Carney et al. 1985). Both stars also lie above the main sequence. Thus, there is observational proof for the presence of at least two binaries among the blue giants and Be stars.

Pols & Marinus (1994) performed Monte-Carlo simulations of binary-star evolution in young open clusters and compared their results to Galactic open clusters. They consider four different types of mass transfer and assume a binary fraction dependent on the initial mass-ratio distribution (overall 25 to 30 % binaries among B-type stars). For young open clusters, their models reproduce the observations very well. The binaries cause the main sequence to be widened, or even a second, binary main sequence to appear. Blue stragglers form as result of mass exchange in close binaries, which may also lead to the formation of Be stars. The blue stragglers can either appear as single stars with fully coalesced components, or have stripped main-sequence companions, He-star companions, or white dwarfs or neutron stars, depending on the closeness of the system and the initial masses and mass ratios of the components. The blue stragglers are rapid rotators. Stars rejuvenated by accretion of matter often appear not only brighter but also bluer than the main sequence.

The simulations of Pols & Marinus elegantly explain the features we see in the CMDs and H-R diagrams of NGC 330. Combining the previously described effects of rapid rotation and multiplicity with various forms of mass exchange, they account for a widened main sequence, for blue giants that emerge as blue stragglers, for blue giants vertically above or even to the blue of the main sequence, and for (some of the) Be stars among the blue stragglers and fainter main-sequence stars.

Additional observational tests can be carried out to check predictions of the models. Apart from the spectroscopic survey for He stars suggested above, X-ray data of the NGC 330 re-

Table 3. Comparison of CNO abundances in the Milky Way, the LMC, the SMC, and NGC 330. "RD" denotes the results of Russell & Dopita (1992), "LL" stands for Luck & Lambert (1992), "BSSM" for Barbuy et al. (1991), "JT" for Jasniewicz & Thévenin (1994), "MBP" for Meliani et al. (1995), "GA" for Grevesse & Anders (1989), Dufour for Dufour (1984), and "RD90" for Russell & Dopita (1990). "DBFL" denotes Dufton et al. (1990), "JSWB" indicates Jüttner et al. 1993, "RDFHI" stands for Rolleston et al. (1993), "LDMPN" for Lennon et al. (1996). For the B stars, the third row of the headers gives names of individual stars, and the fourth row gives their spectral classifications. Note that with the exception of NGC 330, no nitrogen lines were found in the SMC B main-sequence stars. The carbon abundances for all stars may be affected by non-LTE effects. Typical errors for Magellanic Clouds abundances are ± 0.2 or ± 0.3 for individual stars. When names of individual stars are not listed, the abundances refer to mean values. Since spectroscopic abundances are still subject to many uncertainties, only results obtained with the same models and methods are directly comparable.

	A,F,G, and K supergiants								Sun	H II regions	
Element	Milky Way	LMC field		SMC field		NGC 330				LMC	SMC
log ϵ(M)	LL	RD	LL	RD	LL	BSSM	JT	MBP	GA	Dufour/RD90	
	45 stars	4 stars	15 stars	5 stars	11 stars	3 stars	10 stars	5 stars			
C	8.15	8.04	7.97	7.73	7.65	7.7	8.0	7.7	8.6	7.90	7.16
N	8.47		8.36		7.72	6.9			8.0	7.07	6.55
O	8.61		8.68		8.21	7.9			8.9	8.13	8.37
	B giants and main-sequence stars										
	Milky Way	NGC2004	SMC field			NGC 346		NGC 330			
	DBFL	JSWB	RDFHI		JSWB	RDFHI		JSWB		LDMPN	
		D12	AV304	IDK-D2	AV175	11	637	B30	B22	A01	B04
			B0 V	B2 III	B III	B0 V	B0 V	B1 II	B3IIe	B0.5III/Ve	B2IIIe
C	8.2	8.00	6.9	7.1	7.68	<6.9	6.8	7.78	7.79	6.9	6.9
N	7.8	7.54	<6.9	<7.1	7.40	<7.6	<7.2	6.92	6.97	7.7	7.7
O	8.9	8.14	8.2		8.26	8.0	8.0	7.79	7.98	8.0	8.0

gion should be investigated for evidence of B or Be stars with neutron-star or white-dwarf companions, which show a different spectral signature than X-ray flares originating in the disks of Be stars (Cassinelli & Cohen 1994). The models of Pols & Marinus also predict that for many binaries radial-velocity variations are so small that they may escape detection, and in fact *no* indications for binarity were found in previous radial velocity studies (Feast & Black 1980, Carney et al. 1985). Long-term photometric monitoring of NGC 330 similar to the four-year study of the surrounding field population carried out by Sebo & Wood would give further clues about the nature of various types of binaries in NGC 330 in addition to the short-term variability studied by Balona (1992).

7. Is NGC 330 an exception?

NGC 330 is exceptional in at least one respect: it contains the highest fraction of Be stars of any young cluster investigated so far (Grebel et al. 1994b).

However, NGC 330 is not unique in containing what we have named blue giants. The young LMC cluster NGC 2100 seems to contain several stars that could qualify as "blue giants". Böhm-Vitense et al. (1985) analyzed IUE spectra for a number of blue stars in NGC 2100. The stars C13 and B20 (Robertson's numbers, Robertson 1974) have quite low surface gravities though Böhm-Vitense et al. refer to B20 as a main-sequence star. From their placement in the H-R diagram the stars B20, C13, and C31 could be "blue giants" since all of them lie in the post main-sequence region that is traversed very quickly. Admittedly, these are very few stars in comparison to NGC 330. Additional candidates should be investigated.

Analyzing IUE spectra of blue stars in the young LMC cluster NGC 2004, Caloi & Cassatella (1995) find about eight stars lying in the post main-sequence gap. In a CMD, these stars lie at the apparent upper end of the main sequence, just as in NGC 330. Indeed, if we fit an isochrone to CMDs of NGC 2004 (Fig. 1 in Grebel et al. 1994b) we find the main-sequence turnoff at lower magnitudes in good agreement with where Caloi & Cassatella find the first probable main-sequence stars.

Our own photometry of the young LMC cluster NGC 1818 (Grebel et al. 1994b, Grebel 1995) as well as the study by Will et al. (1995) indicates that here as well there is a number of "blue giants" above the main-sequence turnoff and below the position of the blue supergiants. In fact, the CMDs of Will et al. show a forked "upper main sequence" with one group of stars shifted toward red colours, while the other group of stars looks like a slightly blueward extension of the main sequence.

The H-R diagrams for the young field population of SMC (Garmany & Fitzpatrick 1989) and LMC (Fitzpatrick & Garmany 1990) show a possibly related effect: The post main-sequence gap is not, as one would expect from stellar evolution theory, empty but instead well filled with stars. It is quite

possible that this is at least partly the same phenomenon we observe in NGC 330 and several other young Magellanic Cloud clusters. We emphasize that in selecting their stars, Fitzpatrick & Garmany (1990) excluded all known emission-line objects, while in NGC 330 the majority of stars filling the Hertzsprung gap shows Balmer emission. Possible sources for erroneous placement in the Hertzsprung gap of the Magellanic Cloud field stars are discussed by Tuchman & Wheeler (1990).

It also has to be emphasized that all currently widely available evolutionary tracks and isochrones consider slow-rotating, single star evolution only.

In Galactic open clusters, widened main sequences, binary main sequences, and blue stragglers are well-known phenomena and common to clusters of all ages (Mermilliod 1992). It is hardly surprising that the same effect should exist in the Magellanic Clouds. We suggest that blue giants or blue stragglers may be a common feature in young Magellanic Cloud clusters (and possibly in clusters of all ages). This possibility should be carefully investigated since it has significant implications for the determination of ages and IMFs in the Magellanic Clouds.

8. Re-evaluation of the upper slope of the IMF

The true nature of the stars at the apparent upper main sequence is of great significance for the determination of IMFs. If the blue giants are all rapidly rotating single stars and single Be stars, the upper IMF will include stars of erroneously high masses since the inclination angle of a rapid rotator may shift it by up to one magnitude in M_V, which in turn implies a higher luminosity in the H-R diagram and a higher mass.

If the blue giants are binaries it becomes almost impossible to estimate their mass from their position in the CMD/H-R diagram. Their current position is determined by the past mass exchange episodes and various evolutionary effects. We usually do not have information about the current state of the companion, nor do we know the initial mass ratio (see also discussion in Clarke & Pringle 1992), which would be needed for the determination of the IMF. Unresolved binaries may easily result in giving too large a weight to the upper mass bins of the IMF if the star consists of two (or more) components that initially had roughly the same mass. Unrecognized neutron-star or white-dwarf companions may lead to an underestimate of the mass of the visible component.

If instead the blue giants are evolved stars, the upper mass bins of the IMF will be underestimated since the masses of the main-sequence progenitors are likely to have been higher. However, as discussed we think we can exclude that these stars are evolved.

If the binary fraction is known, one can make assumptions about the frequency distribution of different mass ratios and the contribution of these components to the IMF. Detailed comparisons with the predictions of the models of Pols & Marinus (1994) may help to constrain the binary fraction and the types of mass transfer. However, since stars do not need to be binaries to become Be stars and since NGC 330 is so rich in Be stars, we may see the combined result of two different effects: the rotational distortion and red excess for single Be stars, and the main-sequence widening and blue (Be) stragglers due to binarity. At this point, we do not see how these effects can be disentangled. Some of the Be stars may indeed be single stars, since Balona (1992) found a number of λ Eri variables among them, which are not considered binaries. On the other hand, the majority of the Galactic Be stars (Slettebak 1988) appear to be Be stars.

Thus in addition to observational uncertainties and crowding, the determination of the IMF of NGC 330 is severely affected by the above described effects, probably even more so than other Magellanic Cloud clusters because of its high fraction of Be stars. As Massey et al. (1995) point out, spectral classifications in addition to photometry are a prerequisite for any IMF determinations but as we have seen not even spectroscopy can give all the necessary information. We are still far from knowing "typical" IMF slopes, let alone how the IMF varies in different (metallicity) environments since especially binary fraction and binary mass ratios are unknown. Synthetic CMDs, e.g., of Pols & Marinus may help with these problems, however, in the case of NGC 330 the code would need to be adjusted such that single Be-star evolution and binary Be-star evolution is taken into account. Even then, reproducing what we see in NGC 330 would not necessarily lead to conclusive answers since there are many free parameters (such as binary fraction, rotational velocities, initial mass ratios, Be-star fraction and Be lifetimes) so that several combinations may reproduce the observed result. Attempts to reproduce observed CMDs of four young LMC clusters with synthetic CMDs assuming binary fractions between 0 and 50% have been made by Subramaniam & Sagar (1995). They note that in some cases, quite extreme binary fractions are required to reproduce the observations. Subramaniam & Sagar did not account for Be stars in the synthetic CMDs.

9. The age calibration of Magellanic Cloud clusters

The age calibration of Magellanic Cloud clusters is an important input parameter for population synthesis models. Ages of Magellanic clusters are in part based on integrated colours, a rather crude method, and in part on CMDs obtained photographically or by CCD photometry. Ages obtained from the CMDs and isochrone fitting are being used to recalibrate ages based on integrated colours. Integrated colours, in turn, provide an essential input base for population synthesis models. The properties of young clusters in particular are important for modeling active galaxies and starburst galaxies.

For example, Bica et al. (1990) investigated integrated spectra of LMC and SMC clusters in the red and far-red (560–1000nm). They dated the red-supergiant phase to occur between 7 and 12 Myrs. As we have shown, however, the much older cluster NGC 330 is heavily dominated (85% contribution in the K band) by red supergiants (Grebel 1995, Grebel et al. in prep.). Bica et al. (1990) based their age derivations on the integrated Johnson $(U-B)_0$ and Gunn $(u–v)_0$ colours and the apparent main-sequence turnoff visible in CMDs. Young Mag-

ellanic Clouds clusters with a high Be star content like NGC 330 may appear bluer in integrated light due to the UV excess of some of these bright stars, than one would expect for a cluster of the same age without Be stars. Furthermore, a contribution to the UV flux may come from He stars formed in binary interactions (Pols et al. 1991, Pols 1994, Pols & Marinus 1994). Thus these clusters may be dated younger than they really are.

The age calibration of young Magellanic Cloud clusters will be off if blue stragglers are generally present, as they are in young Galactic open clusters. If only photometric data with one colour index are used, unrecognized blue giants may place the turnoff region up to a magnitude or more too bright (s. Carney et al. 1985, Sect. 2), depending on the age of the cluster. Obviously, this leads to a systematic underestimation of the cluster age. The exact age that is derived strongly depends on the parameters of the underlying stellar models (see Chiosi et al. 1995).

A first indicator for blue stragglers is the presence of stars above the main sequence and below the blue supergiant locus, if isochrones are fitted such that they include both the main-sequence band and the loci of blue and red supergiants. In fact, our simultaneous isochrone-fitting technique Roberts 1996) in several colours does not accept the blue giants as part of the main sequence, and this is how we first identified them as anomalous, without spectroscopy. In absence of spectroscopy or multi-colour photometry, blue stragglers will not be recognized for what they are so that age spreads will be derived to fit their positions by isochrones as well (Sect. 2).

The second implication of our findings on the age of NGC 330 is that an age spread, if present, is small and within the uncertainty of the age derived for NGC 330 from isochrone fitting that includes the supergiants. The stars in NGC 330 may be considered coeval within ± 4 Myr (Grebel 1995, Grebel et al. in prep.).

If blue stragglers are generally present, large age spreads need no longer to be invoked to explain the morphology of a CMD. Lack or presence of a considerable age spread in clusters will have important ramifications for theories of star formation. We believe that once spectroscopic data are available for a larger set of clusters, previously inferred age spreads will be much reduced.

10. Concluding remarks

The discovery of blue giants in NGC 330 implies that this cluster is older than has been derived in several previous studies (main-sequence turnoff is shifted to fainter magnitudes) and that the previously inferred large age spread (e.g., Chiosi et al. 1995) is much smaller. The location of the blue and red supergiants is in agreement with the main-sequence turnoff inferred from spectral classifications and isochrone fitting.

We reject the possibility that these stars are subgiants evolving from the main sequence towards the red-supergiant phase, since evolution proceeds so rapidly that it is unlikely to catch stars in this phase. Considering that high-resolution spectroscopic studies of blue giants in NGC 330 did not show enhancement of both He and N and the accompanying C and O deficiency, we argue that the blue giants probably are not evolved stars such as post-red supergiants.

We argue that rotational displacement effects due to rapid rotation and properties of Be stars, which is what most of the blue giants are, can account for their position in the H-R diagram. Departures from spherical symmetry as discussed by Collins (1987) prevent the measurement of global $T_{\rm eff}$ and $\log g$ values and may, depending on the inclination angle, make stars appear as giants. We find that the simulations of the effects of binaries on CMDs of young clusters by Pols & Marinus (1994) describe the observed CMD and H-R diagram morphology very well. These models account for a strongly widened main sequence, the presence of Be stars, and blue unevolved stars above the main sequence through binary interactions and mass transfer that lead to the formation of blue stragglers.

We suggest that the blue giants are most likely a mixture of (1) rapidly rotating B/Be stars of varying orientation and (2) blue stragglers formed by interactions in binary systems. Both possibilities are compatible with these stars being core H burning. Faint short-periodic early-type eclipsing variables and blue straggler binaries have been found in the surroundings of NGC 330 (Sect. 6.4), and we suggest additional observational tests to quantify the binary presence in NGC 330. Isochrones in the observational plane considering a certain binary fraction and rotational displacement rather than representing low-rotation, single-star evolution would be most useful.

We discuss evidence that NGC 330 is not an exception in containing "blue giants", and that blue stragglers are possibly also present in NGC 1818, NGC 2004, and NGC 2100. We argue that unrecognized blue stragglers and binaries can severely impair the determination of IMFs. They can also lead to an underestimation of the ages of young Magellanic clusters and to the derivation of erroneously large age spreads in star formation times, as happened in the case of NGC 330.

Acknowledgements

EKG gratefully acknowledges valuable discussions with Jon & Karen Bjorkman, Steve Cranmer, Katy Garmany, Reinhard Hanuschik, and Rens Waters, who directed me to useful references that helped to uncover the probable nature of the blue giants in NGC 330. We are grateful to Danny Lennon for making available his results prior to or during publication. We thank Klaas de Boer for a critical reading of the text and our referee, Dr. V. Caloi, for useful comments.

EKG was supported through a Graduate Fellowship in the Graduiertenkolleg "The Magellanic System, Its Structure, And Its Interaction With The Milky Way" of the German Research Foundation (DFG). WB was supported by the German Research Foundation (DFG) under grant Yo 5/16–1. This research has made use of the Simbad database, operated at CDS, Strasbourg, France, and of the NASA Astrophysics Data System, operated at CfA, Harvard, USA.

References

Arp, H., 1959, AJ 64, 254
Balona, L. 1992, MNRAS 256, 425
Barbuy, B., Spite, M., Spite, F., Milone, A. 1991, A&A 247, 15
Beech, M., Mihalas, R. 1989, A&A 213, 127
Bessell, M.S. 1991, IAU Symp. 148 "The Magellanic CLouds", Eds. R. Haynes & D. Milne, Kluwer, Dordrecht, p. 273
Bessell, M.S., Wood, P.R. 1993, in "New Aspects of Magellanic Clouds Research", Eds. B. Baschek, G. Klare, J. Lequeux, Springer Lecture Notes in Physics 416, p. 271
Bica E., Alloin D., Santos Jr. J.F.C. 1990, A&A 235, 103
Böhm-Vitense, E., Hodge, P., Proffit, C. 1985, ApJ 292, 130
Bomans, D.J., Grebel, E.K. 1994, Space Sci. Rev. 66, 61
Brunish, W.M., Truran, J.W. 1982, ApJS 49, 447
Caloi, V., Cassatella, A., Castellani, V., Walker, A. 1993, A&A 271, 109
Caloi, V., Cassatella, A. 1995, A&A 295, 63
Carney, B.W., Janes, K.A., Flower, P.J. 1985, AJ 90, 1196
Cassinelli, J.P., Cohen, D.H. 1994, in "Pulsation, Rotation, and Mass Loss in Early-Type Stars", IAU Symp. 162, Eds. L.A. Balona, H. Henrichs, & J.M. le Contel, Kluwer, Dordrecht, p. 189
Charbonnel, C., Meynet, G., Maeder, A., Schaller, G., Schaerer, D. 1993, A&AS 101, 415
Chiosi, C, Summa, C. 1970, Ap. Space Sci. 8, 478
Chiosi, C, Vallenari, A., Bressan, A., Deng, L., Ortolani, S. 1995, A&A 293, 710
Clarke, C.J., Pringle, J.E. 1992, MNRAS 255, 423
Collier, A.C., Jenkins, C.R. 1984, MNRAS 211, 391
Collins, G.W. 1987, in "Physics of Be Stars", IAU Coll. 92, Eds. A. Slettebak & T.P. Snow, Cambridge University Press, Cambridge, p. 3
Collins, G.W., Smith, R.C. 1985, MNRAS 213, 519
Collins, G.W., Truax, R.J., Cranmer, S.R. 1991, ApJS 77, 541
Davies, R.D., Elliot, K.H., Meaburn, J. 1979, MemRAS 81, 89
de Loore, C., Vanbeveren, D. 1994, A&A 292, 463
Doom, C. 1985, A&A 142, 143
Dufton, P.L., Brown, P.J.F., Fitzsimmons, A., Lennon, D.J. 1990, A&A 232, 431
Dufour, R.J. 1984, in "Structure and Evolution of the Magellanic Clouds", IAU Symp. 108, Eds. S. van den Bergh & K.S. de Boer, Dordrecht, Reidel, p. 353
Eggen, O.J., Iben, I.Jr. 1988, AJ 96, 635
Feast, M.W., Black, C. 1980, MNRAS 191, 285
Fitzpatrick, E.L. 1991, PASP 103, 1123
Fitzpatrick, E.L., Garmany, C.D. 1990, ApJ 363, 119
Fitzpatrick, E.L., Bohannan, B. 1993, ApJ 404, 734
Garmany, C.D., Fitzpatrick, E.L. 1989, in "Physics of Luminous Blue Variables", IAU Coll. 113, Eds. K. Davidson & H.J.G.L.M. Lamers, Kluwer, Dordrecht, p. 83
Gies, D.R., Lambert, D.L. 1992, ApJ 387, 673
Grebel, E.K. 1995, PhD Thesis, Bonn University
Grebel, E.K., Richtler, T., de Boer, K.S. 1992, A&A 254, L5
Grebel, E.K., Roberts, Wm J., van de Rydt, F. 1994a, in "The Local Group. Comparative and global properties", 3rd CTIO/ESO Workshop, ESO Conference & Workshop Proceedings No. 51, Eds. A. Layden, R.C. Smith, & J. Storm, La Serena, p. 148
Grebel, E.K., Roberts, W.J., Will, J.M., de Boer, K.S. 1994b, Space Sci. Rev. 66, 65
Grebel, E.K., Roberts, W.J., Brandner, W., Moneti, A. 1996, in prep.
Grevesse, N., Anders, E., 1989, in "Cosmic Abundances of Matter", AIP Conf. Proc., Ed. J. Waddington, New York, p. 1
Grossman, S.A., Narayan, R., Arnett, D. 1993, ApJ 407, 284
Humphreys, R.M., Kudritzki, R.-P., Groth, H.G. 1991, A&A 245, 593
Jacoby, G.H., Hunter, D.A., Christian, C.A. 1984, ApJS 56, 257 (avail. by anonymous ftp from pandora.tuc.noao.edu)
Jasniewicz, G., Th/'evenin, F. 1994, A&A 282, 717
Jüttner, A. 1993, in "New Aspects of Magellanic Cloud Research", Eds. B. Baschek, G. Klare, J. Lequeux, Lecture Notes in Physics # 416, Springer, Heidelberg, p. 301
Jüttner, A., Stahl, O., Wolf, W., Baschek, B. 1993, in "New Aspects of Magellanic Cloud Research", Eds. B. Baschek, G. Klare, J. Lequeux, Lecture Notes in Physics # 416, Springer, Heidelberg, p. 337
Kippenhahn, R., Weigert, A. 1967, Z.f.Astrophys. 65, 251
Kudritzki, R.P., Groth, H.G., Butler, K., Husfeld, D., Becker, S. 1987, in ESO Workshop on the SN 1987A, European Southern Observatory, Garching, p. 39
Landolt, A.U. 1992, AJ 104, 340
Langer, N., Maeder, A. 1995, A&A 295, 685
Lennon, D.J. 1994, Space Sci. Rev. 66, 127
Lennon, D.J., Dufton, P.L., Mazzali, P.A., Pasian, F., Marconi, G. 1996, A&A, submitted
Lennon, D.J., Kudritzki, R.-P., Becker, S.T., Butler, K., Eber, F., Groth, H.G., Kunze, D. 1991, A&A 252, 498
Lennon, D.J., Mazzali, P.A., Pasian, F., Bonifacio, P., Castellani, V. 1994, Space Sci. Rev. 66, 169
Lennon, D.J., Mazzali, P.A., Pasian, F., Bonifacio, P., Castellani, V. 1995, priv. comm.
Lennon, D.J., Dufton, P.L., Mazzali, P.A., Pasian, F., Marconi, G. 1996, A&A, submitted
Luck, R.E., Lambert, D.L., 1992, ApJS 79, 303
Maeder, A. 1987, A&A 178, 159
Maeder, A., Peytremann, E. 1970, A&A 7, 120
Maeder, A., Peytremann, E. 1972, A&A 21, 279
Massey, P., Lang, C.C., DeGoia-Eastwood, K., Garmany, C.D. 1995, ApJ 438, 188
Mazzali, P.A., Lennon, D.J., Pasian, F., Marconi, G., Castellani, V. 1995, A&A, submitted
Meliani, M.T., Barbuy, B., Perrin, M.-N. 1995, A&A 300, 349
Mermilliod, J.C. 1982, A&A 109, 37
Pols, O.R. 1994, A&A 290, 119
Pols, O.R., Coté, J., Waters, L.B.F.M., Heise, J. 1991, A&A 241, 419
Pols, O.R., Marinus, M. 1994, A&A 288, 475
Reitermann, A. 1989, PhD Thesis, Heidelberg
Reitermann, A., Baschek, B., Stahl, O., Wolf, B. 1990, A&A 234, 109
Roberts, W.J., 1996, in prep.
Roberts, W.J., Grebel, E.K. 1995, A&AS, 109, 313
Robertson, J.W. 1974, A&AS 15, 261
Rolleston, W.R.J., Dufton, P.L., Fitzsimmons, A., Howarth, J.D., Irwin, M.J. 1993, A&A 277, 10
Russell, S.C., Dopita, M.A. 1990, ApJS 74, 93
Russell, S.C., Dopita, M.A. 1992, ApJ 384, 508
Schaller, G., Schaerer, D., Meynet, G., Maeder, A. 1992, A&AS 96, 269
Sebo, K.M., Wood, P.R. 1994, AJ 108, 932
Slettebak, A. 1988, PASP 100, 770
Slettebak, A., Kuzma, T.J., Collins, G.W. 1980, ApJ 242, 171
Stetson, P.B. 1992, "User's Manual for DAOPHOT II", Dominion Astrophysical Observatory, Victoria
Stothers, R.B., Chin, C.-W. 1992, ApJ 390, 136

Stothers, R.B., Chin, C.-W. 1994, ApJ 421, L91
Stryker, L. 1993, PASP 105, 1081
Subramaniam, A., Sagar, R. 1995, A&A 297, 695
Tuchman, Y., Wheeler, J.C. 1990, ApJ 363, 255
Venn, K.A. 1995, ApJ 449, 839
Walborn, N.R.1988,in“Atmospheric Diagnostics of Stellar Evolution: Chemical Peculiarity,Mass Loss,and Explosion”,IAU Coll.108, Ed. K.Nomoto, Springer, Heidelberg, p.70
Walborn, N.R., Fitzpatrick, E.L. 1990, PASP 102, 379 (available by anonymous ftp from astro.princeton.edu)
Walborn, N.R., Lennon, D.J., Haser, S.M., Kudritzki, R.-P., Voels, S.A. 1995, PASP 107, 104
Will, J.-M., Bomans, D.J., de Boer, K.S. 1995, A&A 295, 54

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.